Incentivizing electric vehicles to provide regulation while recharging

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***Abstract*—Electric Vehicles (EV) are drawing tremendous attention, as part of the transition toward environment-friendly transportation. While EV recharging represents a considerable extra load on the grid, they also offer new opportunities in terms of consumption flexibility. In this paper, we use the recharging process of EVs to provide regulation to the grid by varying the instantaneous recharging power. We provide an economic analysis of the incentives at play, including the EV owners point of view (longer recharging durations and impact on battery lifetime versus cheaper energy) and the aggregator point of view (revenues from recharging versus regulation gains). In particular, we analyze the range of regulation rewards such that offering a regulation-oriented recharging benefits both EV owners and the aggregator. Interestingly, we observe that under current market conditions in France, an aggregator could offer regulating EV owners to recharge for 50% cheaper, and still be better off than offering only constant-power recharging.**

***Index Terms*—Smart grid, Electric vehicles, frequency regulation, revenue maximization.**

I. Introduction

Electric vehicles (EV) can be recharged from mains power and have the potential to greatly increase the demand for base-load power from grid systems, according to the International Energy Agency [1]. A key point to tackle this problem is to consider EV recharging not only as conflicting with existing load and a threat to the sustainability of the power grid, but also as an enabler in the transition of the power grid to the so-called Smart Grid. This includes the provision of services such as: distributed energy sources, demand responses units, and regulation service providers, which is the concern of this paper.

In this trend, researchers examine the problem from different perspectives. Focusing on regulation dispatch among EVs, Escudero-Garzas, Garcia-Armada and Seco-Granados [2] suggest a water-filing method (originally used in information theory to maximize the throughput over parallel channels [3]) to minimize the variance of the *state of charge* among user batteries. Sun, Dong, and Liang [4], [5] develop a regulation allocation algorithm that outperforms a greedy algorithm in terms of long-term user welfare. Wu, Mohsenian-Rad, and Huang model the relation between aggregator and EVs as a Stackelberg game [6], [7], and design a pricing mechanism to elicit EVs to voluntarily carry out the services. Among the limitations, let us remark that users in [6], [7] are assumed homogenous, i.e., they have identical preferences. For heterogenous users, a pricing design is provided by Gao, Chen, Wang and Liu [8]: heterogeneity lies in a willingness-to-pay parameter for (re)(dis)charging the battery. The aforementioned schemes all depend on the application of Vehicle to Grid (V2G) technology, which allows EV batteries to discharge energy not only to the car engines but also to all kinds of other electricity appliances. Among the concerns about this approach, one can ask whether users will be willing to trade their surplus energy for money, since this increases the range anxiety. The energy delivery efficiency and its impact on battery sustainability are also of significant importance.

A conservative means lies in offering regulation by modulating the power level during EV recharging. More precisely, when oversupply (resp., supply shortage) occurs, regulation down (resp., up) can be realized by raising up (resp., reducing) the recharging power of EVs. This principle is adopted by Sortomme and El-Sharkawi [9] for maximizing aggregator revenue from EV owners (paying for recharging their cars) and from the grid (paying for carrying out regulation services). In the same vein, Leterme, Ruelens, Claessens, and Belmans [10] design an algorithm that manages a large EV fleet assisting wind farm to maintain a stable output.

In this paper, we propose to vary in real time the EV recharging powers, as a response to regulation signals sent from the local Transmission System Operator (TSO)–with the purpose of trading for remuneration. Unlike the aforementioned recharging-based regulation schemes [9], [10], we entitle EV owners the freedom to decide whether to take the regulating-while-recharging option, after being informed of the stochasticity in the charging power, or to recharge at a constant power level. Our model applies to users that are heterogenous in terms of their sensitivity to recharging powers.

We compare two situations, with each time a revenue-maximizing aggregator:

- in a "simple recharging (*S-charging*)" setting, the aggregator sets a recharging price and EVs are recharged at the maximum power;
- in a "two-options (*S-charging* plus *R-charging*)" setting, the aggregator additionally offers EVs the choice to recharge at a lower price, in exchange for the use of the recharging process to provide regulation to the grid, which we refer to as *R-charging*.

We study EV owners reactions to both settings, and investigate the viability of the "two-options" scenario, together with its impact in terms of user welfare and social welfare. Note that in both settings, the EV owners are free to choose none of the option(s) the aggregator offered, i.e. an alternative of *no_charging* is always available. We give analytical thresholds on regulation prices above which higher revenue is guaranteed for the aggregator by offering both recharging options.

The remainder of this paper is organized as follows. Section II describes the structure of our model, with the actors involved (EVs and the aggregator) and their preferences and possible actions. Section III is dedicated to the optimization of the decision parameters by the aggregator to maximize revenue. In Section IV, we fit our model into a real world market to see whether and when it is applicable. Section V concludes the paper.

II. Model description

We consider an aggregator in charge of several charging stations, who purchases electricity at a wholesale price denoted by t (in \$/kWh), and then set by himself a retail price T_s (in \$/kWh) proposed to EV owners for recharging.

Statistics of vehicle usage [11], [12] point out that passenger vehicles are parked most of the time during a day. It is reasonable to expect a similar phenomenon with EVs, hence a relatively low recharging power can be sufficient to fully recharge a battery, at least for some users. This provides the basic assumption we make, that some EV owners are willing to accept reduced recharging power, for cheaper energy.

On the other hand, the aggregator can take this as an opportunity to increase the revenue. Since lower recharging power is acceptable for some clients, the aggregator can decrease it when it is profitable to do so. This chance can be found in the regulation market, that we describe in detail in the following subsection.

A. Regulation mechanism

In a power grid, the aim of frequency control is to reduce the effect of frequency disturbance caused by imbalance between load and supply. Frequency control occurs over a variety of time scales which can be divided into three types, namely primary, secondary and tertiary control, with time granularity ranging from seconds, minutes to more than half an hour respectively [13]. In this paper, we consider varying the EV recharging power level in order to contribute to secondary control, also known as regulation. Primary control is not optimal since too frequent fluctuations have a negative impact on battery lifetime, and tertiary control is not suitable either because the parking duration and battery capacity may not be sufficient to respond to requests. We consider discretized time, and refer to the time frame of one regulation session as Δ (in hours). Typically we expect to have Δ within 0.1 (6 minutes) and 0.25 (15 minutes).

EV charging being seen as a regulation resource, there should be some margins to increase and/or decrease its consumption. When regulation up (down) is asked by the grid, consumption should be brought down (pushed up). This nomenclature is counterintuitive in our context, because it was defined for *generators* being regulation resources, whereas here the task is accomplished by electricity *consumers*. In our proposal, the aggregator sets a default recharging power P_n, bounded between the minimal power 0[1] and maximal power P_d set by the physical limitations of the charging station. When no regulation is called upon, the aggregator charges the plugged "regulating" EVs with this default power. If a "regulation up" signal is received, the aggregator stops charging those EVs (hence a charging power equal to 0), whereas a "down" signal triggers full-speed recharging (i.e., at the maximal power P_d). We allow the default recharging power to equal the bounds ($P_n = 0$ or $P_n = P_d$) since one-sided regulation is also acceptable.

Although this "increase to ceiling or decrease to bottom" policy regardless of the deviation actually demanded by the TSO is quite arbitrary, it is reasonable because the contribution of one single EV is negligible in the TSO's perspective; even aggregated EVs are not sufficient to meet this demand on their own. For example data from RTE, the biggest TSO in France, show that regulation demand in 30 minutes can easily go over 100 MWh [14], a quantity that could only be absorbed by at least ten thousand EVs doing level 2 recharging (19.2kW [15]) at the same time. With the country currently counting about 30 thousand EVs with only 8600 charging facilities, we find it unlikely that EVs may oversupply regulation capacity in the near future; adjusting more finely the amplitude of the charging power changes is left for future work.

Figure 1 illustrates a comparison between recharging at full power P_d and recharging while reacting to regulation requests, in terms of the recharging power and energy transferred to the EV battery. We denote by C_B the total energy requested by the EV, and by ρ_u (ρ_d) the probability of occurrence of regulation up (down), assumed independent at each regulation period in this paper.

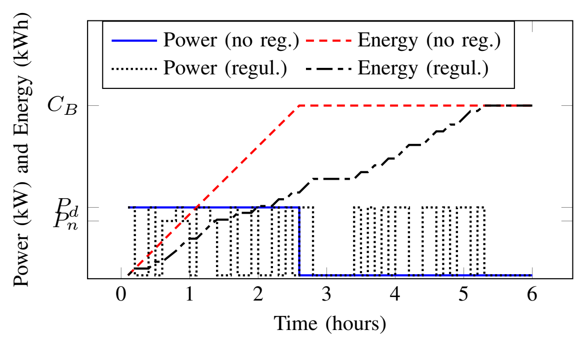

Fig. 1: Power and cumulated energy an EV obtained with and without regulation (simulation with C_B =50kWh, P_d =20kW, P_n =16kW, Δ =0.1hour, $\rho_u = \rho_d$ =0.45)

B. Regulation incentives

Let us turn to monetary compensations. First, the aggregator pays $\Delta t P_n$ per EV per regulation slot. In the case of "up" regulation, the aggregator is additionally payed for reducing demand to 0. The incentive to reduce is denoted in this paper

[1] We do not allow here EVs to deliver energy to the grid (the so-called vehicle-to-grid transfer).

as a fraction $r_u \geq 1$ of the wholesale price: the aggregator thus receives an amount

$$\Delta t r_u (P_n - 0) = \Delta t r_u P_n.$$

In other words, the TSO "re-buys" the energy at a unit price $r_u t \geq t$. As for regulation down, where EVs should consume more than planned, the TSO offers a discount ratio of $r_d \geq 0$ on the normal price t, so that the aggregator buys the extra energy consumed at a reduced price $(1 - r_d)t$, hence it only pays

$$\Delta t (1 - r_d)(P_d - P_n)$$

per EV during each "down" period.

C. Potential revenues from regulation

Putting together all payments and the probabilities of their occurrence, the expected revenue (possibly negative) for the aggregator per regulation slot from one regulating EV is

$$E_r = \Delta t(\rho_u r_u P_n - \rho_d (1 - r_d)(P_d - P_n) - P_n) \quad (1)$$

with the notations recalled below

- t: unit price of energy at which the aggregator buys electricity;
- r_u: remuneration ratio for regulation up;
- r_d: discount ratio for regulation down;
- ρ_u (resp. ρ_d): probability of an "up" (resp. "down") signal, $\rho_n = 1 - \rho_d - \rho_u$ gives the probability that no regulation is needed at this slot;
- P_n (resp. P_d): default (resp. "down") charging power.

D. Aggregator strategic decisions

Initially, the aggregator's freedom is limited to choosing a recharging price and a recharging power, a situation we called *S-charging*. Since users tend to prefer higher powers, we simply assume that the aggregator offers the highest possible power, i.e., the power that we denoted by P_d and which is defined by the physical limitations of the power supply chain.

When the aggregator additionally offers the possibility to recharge while contributing to the regulation service, it has to select separate unit prices for EV users:

- one price T_s (in \$/kWh) for EVs *S-charging*, at the maximum available power.
- one price T_r (still in \$/kWh) for EVs *R-charging*, whose charging process responds to TSO regulation solicitations.

Also, the aggregator would have to choose the default charging power P_n, at which to charge the latter EVs when no regulation signal is received. Those choices will be based on user preferences, assumed known to the aggregator and modeled as below.

E. User preferences

EV owners select the type of recharging that maximizes their utility, which we define here. We assume that the energy demand per EV per day is C_B kWh, and that users tend to prefer the no-regulation charging, for two reasons:

- they prefer to recharge faster, i.e., with higher power;
- and they are reluctant to *uncertainty* in the recharging power (and hence, in the recharging duration) caused by regulations. Additionally, batteries can be sensitive to power variations in the recharging process, another reason for EV owners to be reluctant to contribute to regulation.

For a recharging option, let us denote by $\bar{P}$ the average (expected) charging power and $\delta(P)$ its standard deviation. We define the user valuation (or willingness-to-pay) for a recharging option as

$$V = \theta(\bar{P} - \gamma\delta(P)) \quad (2)$$

where θ is user-specific: a type-θ user has a general sensitivity to power (including its variability) equal to θ. We denote by $\bar{\theta}$ the average value of θ over the EV owner population. The parameter γ represents the reluctance toward power fluctuations, because of the unpredictability of the charging duration and the possible damage to the battery. In this paper, we assume γ is the same for all users, which rather favors the latter interpretation of γ being due to technical aspects. Interestingly, we may see an evolution of γ as the battery technology evolves, with γ getting smaller if batteries tend to be more robust to power variations.

For *S-charging* users, the power is a constant thus $\bar{P} = P_d$ and $\delta(P) = 0$; while for *R-charging* clients:

$$\bar{P} = \rho_d P_d + \rho_n P_n \quad (3)$$

$$\delta(P) = \sqrt{\rho_u \bar{P}^2 + \rho_d (P_d - \bar{P})^2 + \rho_n (P_n - \bar{P})^2)} \quad (4)$$

III. Analysis

Taking the point of view of the aggregator, we are now interested in optimizing the decision parameters to maximize revenue. Using the classical *backward induction* method from game theory [16][2], we first study user reactions to aggregator decisions, and use the result to compute revenue-maximizing decisions.

A. User choices and corresponding aggregator revenue

Adding the monetary aspect (prices paid) to the user valuation defined in (2), we get the user utility function:

$$U = \theta(\bar{P} - \gamma\delta(P)) - TC_B \quad (5)$$

The variable $T \in \{T_s, T_r\}$ is the unit energy price set by the aggregator and chosen by the user. We naturally take $T = 0$ for users who choose *no_charging*.

For notational simplicity, let us write $P_A := \bar{P} - \gamma\delta(P)$: therefore P_A depends on the regulation signals probabilities

[2] we indeed have a leader-follower game, with the aggregator as the leader and users as followers

(ρ_u, ρ_d), the default charging power (P_n), and the user reluctance to variations (γ).

We finally assume that the user sensitivity θ is distributed among EV owners according to an exponential distribution with mean $\bar{\theta}$.

Figure 2 displays user utility for each of the three choices, depending on their sensitivity parameter θ.

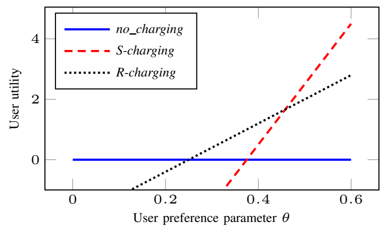

Fig. 2: User utility for the three charging options ($C_B = 50$, $P_d = 20$, $P_A = 8$, $T_s = 0.15$, $T_r = 0.04$): the best choice depends on the user sensitivity θ

Assuming users are rational and choose the option yielding the highest utility, we can simply compare pairs of options: a type-θ user prefers

- "*S-charging*" over "*no_charging*" if $\theta > \frac{T_s}{P_d} C_B$
- "*R-charging*" over "*no_charging*" if $\theta > \frac{T_r}{P_A} C_B$
- "*S-charging*" over "*R-charging*" if $\theta > \frac{T_s - T_r}{P_d - P_A} C_B$.

We have the following two possibilities:

1) If $\frac{T_r}{P_A} < \frac{T_s}{P_d}$ then $\frac{T_r}{P_A} < \frac{T_s}{P_d} < \frac{T_s - T_r}{P_d - P_A}$, so a user would chose *no_charging*, *R-charging*, or *S-charging* when his θ falls into the intervals $(0, \frac{T_r}{P_A} C_B)$, $(\frac{T_r}{P_A} C_B, \frac{T_s - T_r}{P_d - P_A} C_B)$ or $(\frac{T_s - T_r}{P_d - P_A} C_B, +\infty)$, respectively, the limit cases having probability zero.

Let us define $x := P_n / P_d$. The revenue from users choosing *R-charging*, computed in (1), can be rewritten as

$$E_r = \Delta t P_d (\rho_u r_u x - \rho_d (1 - r_d)(1 - x) - x),$$

and we can express the average aggregator revenue R per time unit and per EV, as a function of the proportions α_s and α_r of users choosing *S-charging* and *R-charging*, respectively.

$$R = \alpha_r (T_r + \frac{E_r}{\bar{P}\Delta}) C_B + \alpha_s (T_s - t) C_B \tag{6}$$

From our reasoning above and our assumption of θ being exponentially distributed, we have

$$\alpha_r = \exp(-\frac{T_r}{P_A \bar{\theta}} C_B) - \exp(-\frac{T_s - T_r}{(P_d - P_A)\bar{\theta}} C_B) \tag{7}$$

$$\alpha_s = \exp(-\frac{T_s - T_r}{(P_d - P_A)\bar{\theta}} C_B) \tag{8}$$

2) If $\frac{T_s}{P_d} \le \frac{T_r}{P_A}$, then we can show that $\frac{T_s - T_r}{P_d - P_A} \le \frac{T_s}{P_d} \le \frac{T_r}{P_A}$. A θ-type user then selects *S-charging* if $\theta > \frac{T_s}{P_d} C_B$ and *no_charging* otherwise. Note that the *R-charging* option is never chosen. The aggregator revenue per time unit and per EV becomes

$$R = \alpha_{s0} (T_s - t) C_B \tag{9}$$

with α_{s0} the proportion of EVs choosing the *S-charging*

$$\alpha_{s0} = \exp(-\frac{T_s}{P_d \bar{\theta}} C_B).$$

Since this price setting is equivalent to the *R-charging* option not being offered at all, it will be referred to as the initial case, where only the possibility of recharging without regulation participation is offered to EVs.

B. Maximizing the aggregator revenue

We now seek the optimal strategic decisions from the aggregator point of view.

1) Optimal prices: Summarizing, we have

$$R(T_r, T_s, x) = \begin{cases} \alpha_r (T_r + \frac{E_r}{\bar{P}\Delta}) C_B + \alpha_s (T_s - t) C_B & \text{if} \frac{T_r}{P_A} < \frac{T_s}{P_d} \\ \alpha_{s0} (T_s - t) C_B & \text{otherwise,} \end{cases} \tag{10}$$

where x impacts P_A, and $\alpha_r, \alpha_s, \alpha_{s0}$ depend on prices and on P_A (hence, also on x) as detailed above.

In order to maximize the aggregator profit in (10), we start by optimizing the price pair T_r and T_s, considering x fixed.

When $\frac{T_r}{P_A} < \frac{T_s}{P_d}$ the Hessian matrix is symmetric and negative definite, thus the revenue achieves its maximum at the unique solution of $\frac{\partial R}{\partial T_s} = 0$ and $\frac{\partial R}{\partial T_r} = 0$ [17]; Those optimal prices are:

$$T_s^* = t + \frac{P_d \bar{\theta}}{C_B} \tag{11}$$

$$T_r^* = \frac{P_A \bar{\theta}}{C_B} - \frac{E_r}{\bar{P}\Delta}; \tag{12}$$

when $\frac{T_r}{P_A} \ge \frac{T_s}{P_d}$, i.e. the initial case, aggregator revenue is independent of T_r and maximized at the unique solution of $\frac{\partial R}{\partial T_s} = 0$. Interestingly, this price equals that in (11), meaning that the price of *S-charging* remains unchanged no matter it is offered together with *R-charging* or not.

Note that the optimal price T_r^* is worth applying only when the inequality $\frac{T_r^*}{P_A} < \frac{T_s^*}{P_d}$ holds, otherwise any larger value is equivalent since the option is never selected by users (or equivalently, the aggregator just does not offer that option). As an illustration, we show in Figure 3 the variation of the revenue for T_s and T_r that satisfy $\frac{T_r}{P_A} < \frac{T_s}{P_d}$, while $x = \frac{P_n}{P_d}$ is fixed.

2) Optimal default power P_n: To select the optimal power P_n at which to charge *R-charging* EVs in the absence of regulation signal (or equivalently, the optimal ratio x), we turn to numerical observations because of analytical intractability.

After repeated trials with different combinations of r_d and r_u, we have systematically observed that with the corresponding optimal prices, the revenue seems to be convex in x. A few sample curves are shown in Figure 4. We therefore conjecture that the optimal default recharging power is either 0 or the maximum possible power P_d (i.e., that the optimal x is either 0 or 1). Although we still cannot tell which one performs better, comparing the revenues yielded by both values can be easily done numerically.

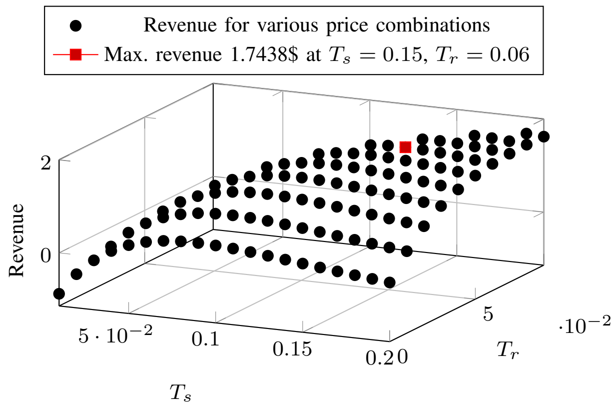

Fig. 3: Revenue as a function of T_s and T_r, $P_n/P_d = 0.8$, $\bar{\theta} = 0.3$, $\gamma = 0.05$, $C_B = 50$, $\rho_u = \rho_d = 0.48$, $\Delta = 0.1$, $t = 0.03$, $r_u = 2.0$, $r_d = 0.6$

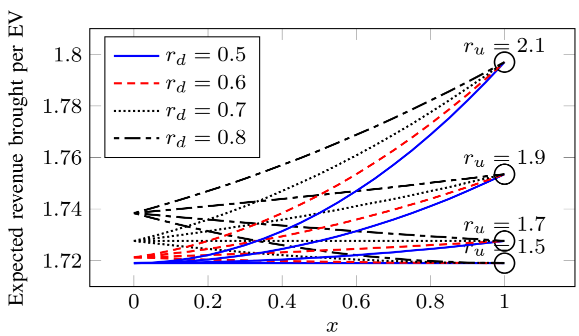

Fig. 4: Aggregator Revenue with multiple combinations of r_d and r_u

C. *When will the aggregator offer an "*R-charging*" option?*

From (10), we can deduce that offering a "*R-charging*" option in addition to the "*S-charging*" one benefits the aggregator only when the mathematical condition $\frac{T_r^*}{P_A} < \frac{T_s^*}{P_d}$ holds, with the prices T_s^* and T_r^* given in (11).

If the independent variables of our model $(t, \rho_d, \rho_u, r_d, r_u, \bar{\theta}, \gamma)$ do not lead to solutions satisfying this inequality, then there is no room for revenue increment for the aggregator. In other words, even if some users are willing to participate to regulation for a discount in their recharging price, the aggregator will not offer that option because the rewards are too low.

We now consider in particular the regulation rewards r_d and r_u, in order to investigate whether EV-based regulation will occur or not in some market. We focus on those values since, being prices, they are easily changeable (from market conditions or from regulation), and the observed values can dramatically differ from one market to another, and also vary significantly over time. Some algebra on the condition $T_r^*/P_A < T_s^*/P_d$ gives us a new form for that condition:

$$\rho_u r_u x - \rho_d(1 - r_d)(1 - x) - x > P_d^{-2}\bar{P}(\bar{P} - \gamma\delta(P)). \quad (13)$$

From previous conjectures on the optimal value for x being 1 or 0, we deduce from (14) two inequalities respectively: $r_u > 2 - \rho_u + \gamma\rho_u^{-0.5}(1-\rho_u)^{1.5}$ and $r_d > 1 - \rho_d + \gamma\sqrt{\rho_d - \rho_d^2}$, at least one of those must hold to enable the aggregator to achieve a higher profit from regulation. We write them in the form of thresholds for r_u and r_d:

$$r_u^{\min} = 2 - \rho_u + \gamma\rho_u^{-0.5}(1 - \rho_u)^{1.5} \quad (14)$$
$$r_d^{\min} = 1 - \rho_d + \gamma\sqrt{\rho_d - \rho_d^2}.$$

When rewards from both up and down regulation are below those thresholds, (14) cannot hold and no *R-charging* option will be offered by the aggregator.

When r_u (resp. r_d) is above the threshold while r_d (resp. r_u) is not, choosing $P_n = P_d$ (resp. $P_n = 0$) earns the aggregator more than the initial case; when both of them are above their thresholds, we cannot tell which one gives higher profit so both $P_n = P_d$ and $P_n = 0$ need to be substituted so that the one yielding the largest revenue can be chosen.

Figure 5 plots user welfare, that is the user utility averaged over all users, who differ in their sensitivity θ. Note that we set $\bar{\theta}$ to 0.3 because this yields a *S-charging* price (T_s^*) of 0.15 \$/kWh, which is the electricity price applied in France.

It is guaranteed that our proposal can never decrease user welfare since *R-charging* just provides one more option without increasing the price of *S-charging*.

Although we don't bring significant increase in aggregator revenue, the energy prices for *R-charging* users are much lower than that for *S-charging*, so users achieve higher welfare from obtaining cheaper energy. For a quite wide region of rewards ($r_u \in [1.5, 2.1]$ and $r_d \in [0.5, 0.8]$), the *R-charging* price (T_r^*) is typically from 38% ($T_r^* = 0.057$ \$/kWh, $T_s^* = 0.15$ \$/kWh) to 48% ($T_r^* = 0.072$ \$/kWh, $T_s^* = 0.15$ \$/kWh) of the *S-charging* price. Finally, comparing Figure 5 with 4 we observe that the x that maximize the aggregator revenue also maximizes user welfare, hence social welfare will also be maximized at the same time.

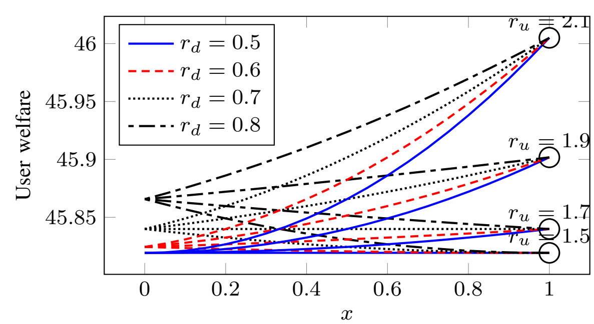

Fig. 5: User welfare with multiple combinations of r_d and r_u

IV. Application in a Real World Market

The form of the thresholds in (15) confirms that a reduced user reluctance (γ) to power variance reduces the thresholds, thus enlarges the region for rewards $\{r_d, r_u\}$ leading to *R-charging* being offered in existing regulation markets. We use empirical regulation up and down probabilities ($\rho_u = 49$, $\rho_d =$

48) found in [14] to calculate the thresholds $r_d^{\min}$ and $r_u^{\min}$, illustrated by the two lines plotted in Figure 6, one for $\gamma = 0.5$ and the other for $\gamma = 0.05$. This restates that if batteries become more robust to power variations, the margin for both aggregators and user to benefit from *R-charging* will increase.

To compare the thresholds with the prices actually settled in a real world market. We plot the ratios of regulation prices over corresponding wholesale electricity prices on the day of July 20, 2015 (data from [14], [18]) as well as daily average prices of that week (from July 20, 2015 to July 26, 2015). Despite the variations of regulation prices within a day, their daily averages can still be above our thresholds, hence some room for the aggregator to contract with the TSO to assure constant and viable regulation prices throughout the day. To illustrate how the aggregator should set the default power P_n, we also show the region where $P_n = 0$ or $P_n = P_d$ is the optimal default charging power for *R-charging*.

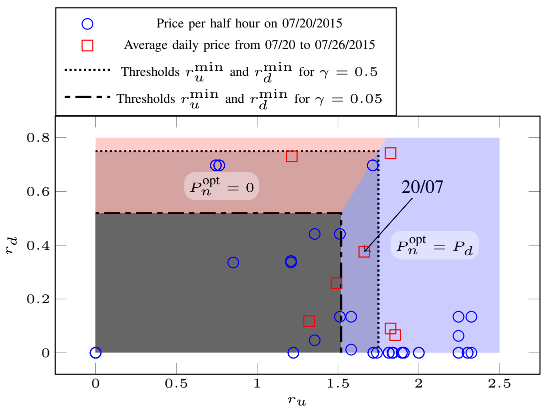

Fig. 6: Observed regulation prices, and thresholds for *R-charging* to be beneficial for the aggregator

V. Conclusion and Perspectives

This paper proposes a control mechanism for an aggregator in charge of several charging stations for Electric Vehicles. We find frequency regulation a promising market for the aggregator, who can provide regulation up (down) by decreasing (increasing) the recharging power of electric vehicles. Following the pricing policy we optimized, not only does the aggregator increase its revenue but also cheaper energy is offered to the EV owners. We highlight that even if EVs appear as a valuable asset for regulation because of their tolerance to changes in the consumed power, the revenue-oriented behavior of aggregators can dramatically affect the extent of regulation effectively provided by EVs. Under reasonable assumptions, the aggregator may even just not offer the possibility to participate in regulation, hence annihilating one of the leverages brought by the advent of EVs. Therefore, the incentives to participate in regulation should be carefully studied, so that the grid actually benefits from the considerable (and distributed) demand flexibility offered by EVs.

Directions for future work include considering competing aggregators (in our study, the aggregator is a monopoly). Another interesting direction is to assume that the potential EV-based regulation supply exceeds the grid needs, leading to dispatching problems for the regulation capacities and revenues. This could be the case in an isolated grid or micro-grid with small regulation demand.

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